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The American Oyster as a Coastal Zone Pollution Monitor: A Pilot Study[1]

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ABSTRACT: The Condition Index [(dry meat weight)(100)/(internal cavity volume)] has been analyzed and compared in the American oyster, *Crassostrea virginica*, from two South Carolina estuaries, one of which was considered polluted by coliform bacteria standards. During the warmer months, oysters from the unpolluted habitat showed a consistently and significantly higher Condition Index. Best fit and power function regressions of Condition Index on total coliform bacteria levels conform with previously cited effects of pollutants on oysters. Condition Index dropped markedly as the incidence of total coliforms increased toward levels of 100 per 100 ml of water. Our results and the known sensitivity of oysters to a spectrum of pollutants suggest that their condition could be used to monitor waterborne pollution in coastal zone areas.

Introduction

The American oyster, *Crassostrea virginica* (Gmelin), occurs in intertidal and subtidal habitats along the Atlantic and Gulf seaboards. Previous studies (e.g., Lowe et al. 1972; Cunningham and Tripp 1975; Scott and Middaugh 1978) have shown that this oyster is sensitive to a variety of waterborne pollutants.

Monitoring of waterborne pollution represents a major cost in the management and conservation of the coastal environment. One commonly used monitor for coastal pollution is the concentration of coliform bacteria in the water column. Water quality standards are often based upon these concentrations (EPA, 1972). Bacteria concentrations may reflect direct biological pollution and may also indicate the presence of chemical or other pollutants that enable the coliform bacteria to thrive.

The Most Probable Numbers Method, normally used to estimate bacteria counts (APHA 1971), is costly and time-consuming and may involve considerable error because of small sample sizes. Regulatory agencies would benefit from the development of supplemental or alternative pollution monitoring methods that are (1) relatively inexpensive, (2) rapidly performed and hence amenable to widespread routine monitoring, (3) based upon large sample sizes, and (4) responsive to a variety of pollutants and thus capable of indicating where and when more costly and more time-consuming methods may be necessary. We suggest here that the condition of oysters may meet these monitoring needs.

Materials and Methods

Our study used high and low intertidal sites in the polluted Little River Inlet Estuary of Horry County, South Carolina and two similar sites in the relatively unpolluted North Inlet Estuary of Georgetown County, South Carolina. Three complete sets of oyster samples (late spring, midsummer, and early fall) were collected at six- to eight-week intervals between May 27, 1975 and September 24, 1975. Each sample con-

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TABLE 1. Summary data for water temperature, salinity, mean total coliform bacteria concentrations, and mean fecal coliform bacteria concentrations, at each of the four areas sampled for oysters, for each of the three sampling periods. Sources of data for bacteria concentrations.

Time	Station[1]	Water Temperature (°C)	Salinity ‰	Mean Total Coliform Bacteria/ 100 ml.	Mean Fecal Coliform Bacteria/ 100 ml.	Bacteria Data Sources[2]
Late spring	1	25.5	30.0	9	No data	DHEC, 1974
	2	25.0	26.0	7	11	BWBI, 1975
	3	26.0	29.0	810	4	EPA, 1972
	4	26.0	26.0	810	4	EPA, 1972
Mid-summer	1	28.0	31.0	8	6	DHEC, 1973
	2	28.0	31.0	8	8	DHEC, 1973
	3	28.0	32.0	140	4	EPA, 1972
	4	28.5	30.5	140	5	EPA, 1972
Early fall	1	27.0	33.0	6	6	DHEC, 1967–72
	2	26.5	33.5	10	7	BWBI, 1975
	3	27.0	27.5 (rain)	100	5	EPA, 1972
	4	27.5	25.0	100	5	EPA, 1972

[1] Station: 1 = North Inlet Estuary, high intertidal creek bank, silty clay substrate; 2 = North Inlet Estuary, low intertidal creek flat, silty clay substrate; 3 = Little River Inlet Estuary, high intertidal creek bank, silty clay substrate; 4 = Little River Inlet Estuary, low intertidal creek flat, silty clay substrate.

[2] Data Sources: BWBI: Records of Belle W. Baruch Institute for Marine Biology and Coastal Research, University of South Carolina, Columbia, South Carolina 29208; EPA: Agency report of the U.S. Environmental Protection Agency (EPA 1972); DHEC: Records of the South Carolina Department of Health and Environmental Control, Columbia, South Carolina 29201.

tained 50 marketable size (height ≥ 7.6 cm) oysters.

All 600 oysters were cleaned and separated and shell dimensions (to nearest 0.5 mm), shell volumes (to nearest 0.5 ml), and meat weights (to nearest 0.01 g) were carefully analyzed (Westley 1961) so that Condition Index [(dry meat weight)(100)/(internal cavity volume)] could be calculated (Galtsoff 1964). In addition, habitat descriptions and tidal stages, temperature, salinity, and weather in each estuary were recorded for the times of sample collections.

Estimates of mean fecal coliform and mean total coliform bacteria in each of the study areas were obtained from the South Carolina Department of Health and Environmental Control, Columbia, South Carolina; the Belle W. Baruch Institute for Marine Biology and Coastal Research, University of South Carolina, Columbia, South Carolina; and the U.S. Environmental Protection Agency (EPA 1972). Although only the Baruch Institute data were from 1975, records of the other agencies (Table 1) indicated that coliform bacteria levels in the two estuaries were statistically similar during the previous seven to eight years. Monthly averages of bacteria concentrations in the water, during stages of the tide in which the oysters were covered, provided estimates of the bacteria levels to which the oysters were exposed.

Statistical analyses included mean, standard deviation, and standard error of the mean for the dimension, volume, meat weight, and Condition Index measures in each oyster sample. Student's *t*-tests for differences between mean values, and power, simple linear, and multiple linear regressions with goodness of fit determination were also used.

Results and Interpretation

Subsets of the data were examined for significant differences: (1) within-habitat differences (high-high, low-low intertidal) between the two estuaries that may be directly related to pollution levels, and (2) between-habitat differences within each estuary to understand the natural changes possible within the intertidal gradient. Less attention was paid to temporal changes, since growth studies *per se* were not a major goal of this pilot study.

Physical and Bacteriological Data

The two sample areas did not differ physically other than that one was polluted, by coliform bacteria standards (Table 1). The

TABLE 2. Summary data for oyster shell height and internal cavity volume for each of the four stations and three sampling periods used in this study. Results of Student's *t*-test shown when differences were significant ($p < 0.05$* or $p \leq 0.01$**). Refer to Table 1 for description of each sampling station.

Time	Station	Mean Height (cm)	Standard Deviation (cm)	Between-Habitat *t*-test	Within-Habitat *t*-test	Mean Cavity Volume (ml)	Standard Deviation (ml)	Between-Habitat *t*-test	Within-Habitat *t*-test
Late spring	1	10.7	1.3	1 vs 2*		13.9	8.2	1 vs 2*	
	2	10.0	1.0			10.4	3.3		2 vs 4*
	3	10.4	1.5			12.7	5.5		
	4	10.6	1.3			12.8	5.0		
Mid-summer	1	10.8	1.2	1 vs 2**		13.9	5.2	1 vs 2**	
	2	8.8	1.2			8.4	3.0		
	3	10.7	1.9	3 vs 4**		13.7	7.2	3 vs 4*	
	4	9.4	1.3			10.2	3.7		
Early fall	1	11.0	1.9	1 vs 2**		12.4	5.5	1 vs 2**	
	2	9.5	0.9			7.4	2.6		2 vs 4**
	3	11.1	1.5	3 vs 4**		10.8	3.6		
	4	10.1	1.3			10.2	3.8		

mean number of total coliform bacteria per 100 ml was significantly ($p \leq 0.05$) higher in Little River Inlet Estuary (Table 1), probably because of the inadequate treatment of domestic sewage (EPA 1972). By contrast, mean numbers of fecal coliform bacteria per 100 ml in the two estuaries were not significantly ($p \geq 0.05$) different throughout the time of oyster sampling. Low and similar fecal coliform counts for the two estuaries may reflect the high salinities observed in the estuaries (Table 1), as well as the time of year, since the reaction and chemistry of highly saline water do not favor the survival of *E. coli*, and *E. coli* is less viable in seawater in summer than in winter (Carlucci and Pramer 1960; Vaccaro et al. 1950).

Dimensional Measures

The height measurements are representative of our dimensional analyses (Table 2). No significant differences in oyster height were found in within-habitat comparisons of North Inlet and Little River oysters, in both high and low intertidal zones. In North Inlet Estuary, the mean height of high intertidal oysters was significantly ($p \leq 0.05$) greater than that of low intertidal oysters at all three sampling times. This was true also of Little River Inlet Estuary oysters, except for the late spring sample. Our observations and previous studies (Battle 1891; Dean 1891; Korringa 1952; Galtsoff 1964) indicate that oysters from the highest intertidal region in many southeastern estuaries are clustered and crowded, giving rise to a more elongate shell form than that of oysters growing lower in the intertidal zone. Therefore spatial crowding, rather than any possible age differences, might explain the greater height values in the high intertidal oysters.

Cavity Volumes

The internal cavity volumes differed between-habitat and within-habitat (Table 2). For North Inlet Estuary, the mean cavity volume of high intertidal oysters was significantly ($p \leq 0.05$) greater than that of low intertidal oysters at each sample time, but this was true in Little River Inlet oysters only in the midsummer sample. Thus, shell elongation always produced a greater internal cavity volume in North Inlet oysters, but not in Little River Inlet oysters.

In the low intertidal zone, mean cavity volume of Little River Inlet oysters was significantly greater than that of North Inlet oysters in the late spring and early fall, but not in midsummer; cavity volumes in the three sets of high intertidal samples were not significantly different (Table 2). Thus, dimension-to-volume relationships at the two sample areas were different, and regional within-habitat volume differences also occurred. We believe valve thickness best explains these differences and are now investigating this possibility.

Meat Weights

Mean dry meat weights showed major differences between oysters from the two

TABLE 3. Summary data for dry meat weight and Condition Index for each of the four stations and three sampling periods used in this study. Results of Student's *t*-test shown when differences were significant ($p \leq 0.05$* or $p \leq 0.01$**). Refer to Table 1 for a description of each sampling station.

Time	Station	Mean Dry Meat Weight (g)	Standard Deviation (g)	Between-Habitat *t*-test	Within-Habitat *t*-test	Mean Condition Index	Standard Deviation	Between-Habitat *t*-test	Within-Habitat *t*-test
Late spring	1	1.04	0.39	1 vs 2**	1 vs 3**	8.4	3.2	1 vs 2**	1 vs 3**
	2	0.57	0.17		2 vs 4*	11.3	5.0		2 vs 4*
	3	0.49	0.17			4.1	1.3		
	4	0.47	0.16			3.7	1.2		
Mid-summer	1	0.74	0.26	1 vs 2**	1 vs 3**	5.8	1.5	1 vs 2**	1 vs 3**
	2	0.58	0.21		2 vs 4*	7.6	3.0		2 vs 4**
	3	0.55	0.24			4.4	1.9		
	4	0.45	0.20			4.7	1.9		
Early fall	1	0.69	0.30	1 vs 2**	1 vs 3**	6.0	2.5		1 vs 3**
	2	0.48	0.12			7.1	2.5		2 vs 4**
	3	0.50	0.14			4.8	1.4		
	4	0.51	0.17			5.0	1.7		

estuaries (Table 3). In North Inlet Estuary, the mean meat weight of high intertidal oysters was consistently and significantly ($p \leq 0.01$) greater than that of low intertidal oysters, suggesting that environmental factors associated with the intertidal gradient (such as length of exposure and hence length of feeding, number of competitors) may strongly affect meat production in North Inlet oysters. In Little River Estuary, meat weights in the three sets of data were not significantly ($p \geq 0.05$) different. Here, factors operating throughout the intertidal gradient may most strongly affect meat production.

In the high intertidal zone, mean meat weight of North Inlet oysters was significantly ($p \leq 0.01$) greater than that of Little River oysters in all three sample sets. With the exception of the early fall sample, the same pattern (with significant ($p \leq 0.05$) differences) occurred in the low intertidal zone. We attribute the midsummer to early fall meat increases in Little River Inlet low intertidal oysters to the accumulation of gonadal tissue, since oyster spatfall in the Little River area was not observed until after the early fall sampling period. The lowered meat weights in Little River Inlet oysters also suggest a lowered physiological condition, which is further reflected in the Condition Index.

Condition Index

The mean Condition Indices ranged from 3.7 to 5.0 in Little River Inlet Estuary, and from 5.8 to 11.3 in North Inlet Estuary (Table 3). These non-overlapping ranges are the most striking difference between oysters of the two estuaries. Condition Indices of high and low intertidal oysters from North Inlet Estuary were significantly ($p \leq 0.01$) higher than those of oysters from similar Little River Inlet habitats.

In Little River Inlet Estuary, no significant between-habitat differences in Condition Index were observed; here, as with meat production, the most important factors influencing condition must operate throughout the intertidal gradient. In North Inlet Estuary in the late spring and midsummer samples, mean Condition Index of the low intertidal oysters was significantly ($p \leq 0.05$) higher than that of high intertidal oysters, even though mean meat weight in the high intertidal zone was significantly higher (Table 2). This disparity appears because the use of mean values obscures the relative effects of cavity volume and meat weight in individual oysters. By analyzing subsamples from each estuary and, thus, comparing oysters with similar dimensions and similar cavity volumes or meat weights, we determined that meat weights, and not cavity volume differences, were responsible for the observed differences in Condition Index. Thus, the higher Condition Indices at North Inlet reflect increased meat production and suggest better physiological condition existed in that area's oysters.

Because pollution, as measured by bacteria standards, was the primary difference

between the two estuaries, regressions of Condition Index on total coliform bacteria were calculated. Best fit and power function ($y = ax^b$) regressions, shown in Fig. 1, suggest that condition diminishes markedly as bacteria accumulations increase toward 100 per 100 ml water.

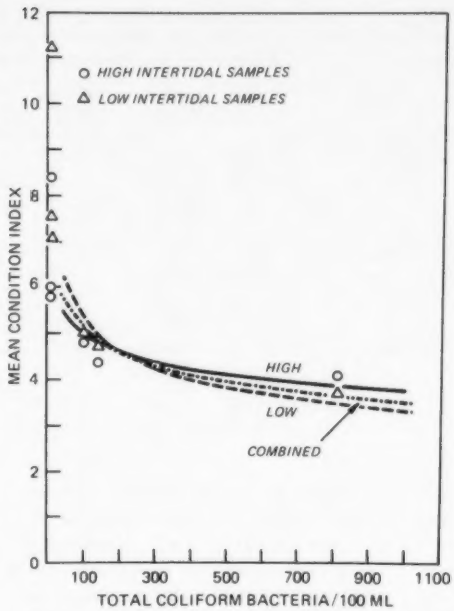

Fig. 1. Best fit and power function regression relating oyster Condition Index to total coliform bacteria densities in the two studied South Carolina estuaries. $r = 0.93$. Note the high negative slopes at lower bacteria concentrations, and subtle differences between condition of high and low intertidal oysters at higher bacteria concentrations.

Discussion

This study suggests that contamination of estuarine waters does produce measureable differences in the growth and condition of American oysters, Condition Index being significantly higher in oysters from relatively unpolluted environments. These differences arise from a decrease in meat production as pollution levels, marked by coliform bacteria, rise.

Numerous factors affect the Condition Index of oysters, including the species involved, age of the oysters, temperature and other seasonal changes, stage of gonadal development, water depth, salinity, nature of substrate, population density and available food, and associated organisms, as well as pollutants (Loosanoff and Engle 1942; Beaven 1946; Korringa 1952; Ito and Imai 1955; reviews in Haven 1961 and Galtsoff 1964; Bartsch et al. 1967). Thus, when comparing the condition of oysters in different estuaries, we took special care to identify many of these factors so that comparisons were meaningful (see Galtsoff 1964).

The oysters from Little River Inlet Estuary and North Inlet Estuary lived in similar microhabitats, and were subjected to similar seasonal salinity and temperature regimes. Compared oysters were of the same sizes (and, by inference, ages), and high intertidal oysters from each estuary were more elongated because of their crowded, clustered habit.

Reproductive periods in oysters did affect their condition, but these changes were not synchronous at Little River and North Inlet and cannot explain the consistently lowered condition of oysters from the Little River Inlet area.

Only one difference in associated organisms was observed; bristleworms, *Polydora websteri*, common inhabitants of oyster shells in the Little River Inlet area, were virtually absent from shells in the North Inlet area. Polydorids can indeed lower the condition of oysters (Lunz 1940, 1941), yet we believe that the lower Condition Index in Little River Inlet is related to pollutants. The presence of polydorids may, in fact, be dependent upon the presence of pollutants in the water column and within the oysters. Reish (1955) found that, in contrast to many other polychaete worms, a species of *Polydora* was more prevalent in polluted than in nonpolluted areas of San Pedro Bay, California.

Additional complexities appear when the effect of bacteria themselves are considered. Possible effects include: (1) oysters may accumulate bacteria (and other pollutants) in concentrations higher than those in the surrounding waters; (2) high bacteria concentrations may require oysters to produce copious mucus sheets to expel bacteria; (3) these bacteria (or mucus) concentrations may interfere with the feeding processes of oysters; (4) oysters may even

cease feeding during periods when they contain bacteria in high concentrations. Galtsoff and Arcisz (1954) indicated that high (≤5,000 per ml) concentrations of *E. coli* did not affect the pumping rate of adult oysters, yet their acute (90 h) laboratory experiments, using only two oysters, may be inapplicable to the long-term evaluation of naturally occurring oyster populations. Similarly, Loosanoff and Engle (1947) reported that only very high ($\simeq 2 \times 10^6$ per ml) concentrations of *Chlorella* reduced pumping rates in adult oysters. Such studies, using single species cultures, are important in mariculture and other work (Tenore and Dunstan 1973) but are of doubtful application to natural settings where a diverse microbiota occurs in the water column. Viruses, bacteria, plankters, and their metabolic by-products may co-occur (Loosanoff and Engle 1947; Davids 1964; Metcalf and Stiles 1968; Mitchell 1971; Fugate et al. 1975) even in waters of approved shellfishing areas, and the combined effects of these factors on the pumping and feeding of oysters are still incompletely known. As microbiota concentrations (in μg C per l) increase above those typical for the natural environment, the relative feeding rate (% C removed/dry meat weight) of oysters remains constant, their biodeposition rate (pseudofeces production) increases, and their assimilation efficiency (% utilization of filtered food particles) decreases (Loosanoff and Engle 1947; Tenore and Dunstan 1973; Widdows et al. 1979). Although details remain to be worked out, the deleterious effects of high microbiota concentrations upon oyster feeding are obvious from these findings. Indeed, "saturation" of tissues with microbiota may occur as microbiota concentrations rise. Our data (Fig. 1) suggest that this "saturation" occurs when these concentrations, as reflected in coliform bacterial counts, reach the range of 50–200 per 100 ml, with condition remaining low but relatively unchanged as additional microbiota are added to the water. At these higher levels, the oysters would expend considerable energy in particle expulsion through pseudofeces, thereby making additional meat production difficult.

Other studies (Newlands and Ham 1910; Fisher and Acker 1935; Prescott et al. 1945; Clague and Almario 1952) have suggested that the concentration of bacteria within oysters may depend upon the tidal position of the oysters, and the temperature and metabolic activity of the oysters, as well as upon the amount of surrounding waterborne bacterial pollution. Our data (Fig. 1) suggest subtle relationships between tidal position of the oysters, the condition of the oysters, and bacteria standards of pollution; the condition of high intertidal oysters became greater than that of low intertidal oysters as total coliform levels increased. These differences, although not significant, suggest that the high intertidal position may be advantageous to oysters that live in polluted habitats, possibly because (1) shorter periods of water filtration may result in fewer pollutants entering the oysters, (2) insolation effects of subaerial exposure may be detrimental to some pollutants including bacteria, and (3) pollution levels, in the higher tidal stage waters, may be decreased by the increased volume of water in an estuary at high tide. These possibilities warrant further study.

Our work and other recent studies (Scott and Middaugh 1978; Scott and Vernberg 1979) clearly suggest that Condition Index analyses deserve increased emphasis. Additional data on the Condition Index of oysters should be gathered and analyzed: (1) over a wider geographic range, (2) over a broader range of estuarine habitats, (3) throughout the year, (4) for single pollutants, and (5) for pollutant combinations acting or working together. Months when oysters are harvested should be emphasized, in order to elucidate the connection between water quality and predictions of marketable yield of oysters in estuaries.

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